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MODERN DARK-FIELD MICROSCOPY AND THE HISTORY OF ITS DEVELOPMENT

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INTRODUCTION

In most work with the microscope the entire field of view is lighted and the objects to be studied appear as colored pictures or as shadows—in extreme cases, as silouhettes—on a white ground As the field is always light, this has come to be known as Bright-Field Microscopy (Fig. 1).

Fig. 1

Fig. 2

Bright- and dark-field photo-micrographs of the same objects (starch grains).

In contrast with this is Dark-Field Microscopy in which the field is dark, and the objects appear as if they themselves emitted the light by which they are seen (Fig. 2).

The study of objects in a bright-field probably comprises 95% of all microscopic work, and is almost universally applicable. On the other hand dark-field microscopy has only limited applicability, and yet from the increased visibility given to many objects it is coming to be appreciated more and more.

Definition.—In its comprehensive sense, Dark-Field Microscopy is the study of objects by the light which the objects themselves turn into the microscope, and none of the light from any outside source passes directly into the microscope as with bright-field microscopy.

There are two principal cases: (A) The objects which are truly self-luminous like phosphorescent animals and plants; burning or incandescent objects, and fluorescent objects. (B) The objects which emit no light themselves, but which deflect the light reaching them from some outside source into the microscope.

These two groups are well represented in Astronomy. If one looks into the sky on a cloudless night, the fixed stars show by the light which they themselves emit, but the moon and the planets appear by the light from the sun which they reflect to the earth, the sun itself being wholly invisible at the time. As there is relatively very little light coming from the intervening space between the stars and planets, all appear to be self-luminous objects in a dark field. This reference to the sky at night will serve to bring out two other points with great clearness: (1) The enhanced visibility. Everybody knows that there are as many stars in the sky in the daytime as at night, but they are blotted out, so to speak, by the flood of direct light from the sun in the daytime, while at night when these direct rays are absent and no light comes from the back-ground the stars and the planets show again by the relatively feeble light which they send to the earth.

(2) The other point is that in dark-field microscopy the objects must be scattered, not covering the whole field (Fig. 2). If there were no intervening empty space the whole face of the sky would look bright

It will be seen from this that ordinary sections or other objects so large that they fill the whole field of the microscope cannot be studied advantageously by the dark-field method, for they would make the whole field bright. But for the liquids of the body, blood, lymph, synovial, and serous fluids, fluid from the cavities of the

nervous system, saliva, and all other mucous fluids, and isolated tissue elements where the solid or semi-solid substances are distributed in a liquid, the appearances given by this method are a revelation as was pointed out by Wenham and Edmunds and many others over fifty years ago. No less is the revelation coming from the study of bacteria, protozoa and other micro-organisms in the dark field.

Dark-Field and Ultra-Microscopy

In both of these the objects seem to be self-luminous in a dark field, and no light reaches the eye directly from an outside source, but only as sent to the eye from the objects under observation.

The terms simply represent two steps, and merge into each other.

Dark-Field Microscopy deals with relatively large objects, 0.2μ or more in diameter, that is, those which come within the resolving power of the microscope.

Ultra-Microscopy deals with objects so small that they do not show as objects with details, but one infers their presence by the points of light which they turn into the microscope. This can be made clear by an easily tried-naked-eye observation. Suppose one is in a dark room, and a minute beam of brilliant light like sunlight or arc light is directed into the room. Unless one is in the path of this beam of light it will remain invisible, but if there are vapor or dust particles present they will deflect some of the light toward the eye and will appear as shining points. The character of the particles cannot be made out, but the points of light they reflect indicate their presence. As Tyndall used this method in determining whether a room was free from dust in his experiments in spontaneous generation, the appearance of the shining dust particles is sometimes called the "Tyndall effect."

The two forms are said to merge, because in studying objects like saliva, etc., with the microscope designed especially for dark-field work, some of the objects seen will show details, but some are so small that they show simple as points of light usually in the form of so-called diffraction discs. The larger objects in the saliva come in the province of dark-field microscopy, and the smallest ones, of ultra-microscopy, and in this case the instrument used might with equal propriety be called a dark-field or an ultra-microscope.

The great purpose of the dark-field microscope is to render minute objects or details of large objects plainer or actually visible

from the advantages offered by the contrast given between the brightly lighted objects and the dark background. For example, with the homogeneous immersion objective the study of fresh blood with the ordinary bright-field method enables one to see the red corpuscles with satisfaction, but the leucocytes are not easily found and the blood-dust (chylomicrons) and the fibrin filaments are not seen at all or very faintly. With the same microscope using the dark-field illumination the leucocytes are truly white cells, and the blood-dust is one of the striking features of the preparation, and the fibrin filaments seem like a delicate cobweb.

In this connection, perhaps a few words should be added on the terms Resolution and Visibility. Both came over from the ancient science of astronomy, and are properly used only when restricted as in astronomy.

By resolution is meant the seeing of two things as two, not blended. For example if two stars are close together they are resolved if they appear as two. When the telescope was invented it was found that many stars that appeared single were really two stars close together. If two lines are placed close together they appear as two to the naked eye when close up, but as one moves away the lines seem to fuse and make one. Visibility refers only to the possibility of seeing a thing. In the above examples the twin stars were visible to the naked eye but not resolved into two, and likewise the lines were long visible after they could be seen as two lines. Now the purpose of the ultra-microscope is solely to increase the visibility of small particles without reference to their details of structure. Dark-field microscopy, on the other hand, while it gives greatly increased visibility, also gives resolution of details.

As with bright-field microscopy the resolution of details of structure depends directly upon the numerical aperture (NA) of the objective, and the brightness upon the square of the aperture (NA^2).

Method of Dark-Field Microscopy

In this article the ultramicroscope and the study of self-luminous objects will not be further considered, but the discussion will be limited to objects which must be lighted by some outside source.

There are two principal cases: (1) objects which are lighted from above the stage of the microscope or by so-called direct light (Fig. 3)

and, (2) objects which are lighted from below the stage, or by transmitted light (Fig. 4).

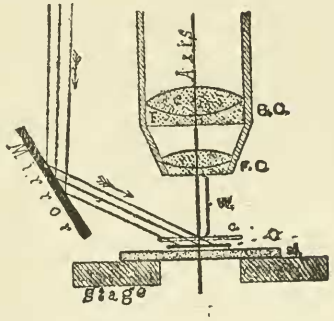

Fig. 3. Light from above the stage. (From *The Microscope*)

In both cases the light from the source is at such an angle that none of it can enter the objective directly but only as it is deflected or "radiated" by the objects in the microscopic field.

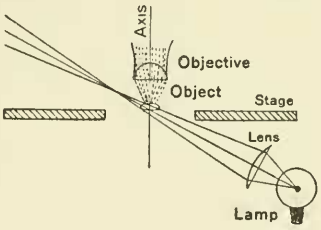

Fig. 4. Light from below the stage.

When the light upon the object is from above the stage the background must be non-reflecting. If the background were white there would be a kind of bright-field, not dark-field microscopy.

The black-background is secured either by placing the object directly upon some black velvet or other non-reflecting surface, or on a glass slide which in turn is placed upon black velvet, etc., or on a dark well. The simplest way to produce a dark-well is to turn the condenser aside and place a piece of black velvet over the foot of the microscope. Or the condenser can be lowered well and the velvet put over the top of the condenser.

Diffuse daylight from a window, or more satisfactorily, artificial light directed by a mirror or lens (bull's eye), is directed obliquely down upon the preparation (Fig. 3). Exactly the same preparation will answer for light from below the stage. In this case the condenser is turned out of the way, and some black-velvet put over the foot of the microscope to cut out stray light.

For a good naked eye demonstration showing the increased visibility due to the dark-field, some cotton may be placed on a piece of black velvet, and a similar tuft of cotton on a white card.

For the special methods of lighting microscopic objects from above the stage, see in the historical summary at the end of this paper.

Dark-Field Microscopy by Transmitted Light.—To make objects appear self-luminous in a dark field when illuminated by beams of light from below the stage, two things are necessary:

(1) The objects must be able to deflect in some way the light impinging upon them into the microscope.

(2) None of the light from the source must be allowed to pass directly into the microscope. These conditions are met when (a) the objects to be studied are of different refractive index from the medium in which they are mounted, and (b) when the transmitted light thrown upon the object is at such an angle that it falls wholly outside the aperture of the objective (Fig. 4-7).

The objects deflect the light into the microscope

(1) By Reflection
(2) By Refraction
(3) By Diffraction

Any one of these will suffice, but any two or all of the ways may be combined in any given case.

For low powers where the aperture of the microscope objective is relatively small it is comparatively easy to make the transmitted beam of so great an angle that none of it can pass directly into the microscope. A simple experiment will show this: A 16 mm. or lower objective is used, the substage condenser is turned aside and on the stage is placed a clean slide with a little starch, flour, or other white powder dusted upon it. If now the mirror is turned to throw the light directly up into the microscope the field will be bright and the objects relatively dark, but if the mirror is turned at an angle suf-

ficient to throw the whole beam at a greater angle than the aperture of the objective will receive, the field will become dark and the starch or flour grains will stand out as if shining by their own light. If some black velvet is placed on the foot of the microscope so no light can be reflected upward into the microscope from the foot or the table, the field will be darker. This experiment succeeds by either natural or artificial light. If some water containing paramecium and other micro-organisms is put on the slide and put under the microscope, the organisms will appear bright and seem to be swimming in black ink.

It is readily seen that with the method just discussed the light is all from one side (Fig. 4). To light the objects from all sides, that is, with a ring of light, the simplest method, and the method utilized in all modern dark-field microscopy, is to use a hollow cone of light, the rays in the shell of light all being at so great an angle with the optic axis of the objective that none of them can enter the microscope directly (Fig. 4-7).

With Refracting Condensers. With the condensers of the achromatic or chromatic type used for bright-field microscopy a solid cone of rays is used. To get the dark-field effect the objects to be studied must be lighted only by the rays at so great an angle that they cannot enter the objective directly. This requires that the condenser shall have a considerably greater aperture than the objective. The ordinary method of making the hollow cone is to insert a dark stop—central stop—to block or shut off the central part of the solid cone of light. The object is then illuminated with a ring of light of an aperture greater than that of the objective (Fig. 6). Some of this light is turned by the objects into the microscope. As only a relatively small amount of the light is deflected by the objects into the microscope, it is evident that there must be a great deal of light to start with or there will not be enough passing from the object to the microscope to make it properly visible. The question also naturally arises how one is to determine the size of the central stop to be used with any given condenser and objective.

This is easily determined as follows: The field is lighted well as for ordinary bright-field observation and some object is got in focus. Then the object is removed and the iris diaphragm of the condenser opened to the fullest extent. If one then removes the ocular and looks down the tube of the microscope and slowly closes

the iris, when the full aperture of the objective is reached, that is, when the back lens of the objective is just filled with light, the opening in the iris represents the size of the central stop to use to cut out all the light which would pass into the microscope from the condenser; all the ring of light outside of this is of too great an angle for the aperture of the objective. One can measure the size of the opening in the iris with dividers and then prepare a central stop diaphragm.

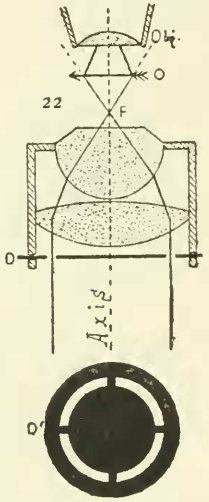

Fig. 5. Ordinary condenser with sectional and face views of the central stop (D). (From *The Microscope*)

A visiting card is good for this. It should be blackened with India ink. To be on the safe side it is wise to make the central stop a little greater in diameter than the iris opening (Fig. 5).

If now the microscope is lighted as brilliantly as possible, and then the iris opened to its full extent and the blackened central stop is put in the ring under the condenser, and a slide used with starch or flour on it, the flour or starch particles will be lighted with the ring of light, and they will deflect enough into the objective to make the objects appear bright as if shining by their own light, the background remaining dark. If the field looks gray or light instead of black it is because the central stop is too small or not centered or the particles used for objects are too numerous, not leaving enough blank space.

One can determine what is at fault thus: The ocular is removed. If the central stop is too small the back lens of the objective will show a ring of light around the outside. If the central stop is not centered there will be a meniscus of light on one side. If the objects are too numerous the whole field will be bright. To verify these statements one can use a specimen with flour or starch all over the slide. It will look dazzlingly light, with the ocular in place and the back-lens will be very bright when the ocular is removed.

For the meniscus of light when the central stop is decentered, purposely pull the ring holding the stop slightly to one side and the meniscus will appear in the back lens. To show the ring of light due to a too small size of the stop, the easiest way is to use a higher objective, say one of 3 or 4 mm. in place of the 16 mm. objective. While it is necessary to eliminate all the light which could enter the objective directly, the thicker the ring of light which remains to illuminate the objects the more brilliantly self-luminous will they appear, therefore one uses only the stop necessary for a given objective. If one makes central stops for the different objectives as described above it will be greatly emphasized that the objectives differ in aperture, in general the higher the power the greater the aperture, and consequently the larger must be the central stop, and the thinner the ring of light left to illuminate the object. As one needs more light for high powers instead of less than for low powers, the deficiency of light caused by the large central stop must be made good by using a more brilliant source of light for the high powers.

Reflecting Condensers. As was first pointed out by Wenham, 1850-1856, refracting condensers are not so well adapted for obtaining the best ring of light for dark-field work as a reflecting condenser, on account of the difficulty in getting rid of the spherical and chromatic aberration in the refracted bundles of such great aperture. He first (1850) used a silvered paraboloid and later (1856) one of solid glass as is now used. Within the last 10-15 years there has also been worked out reflecting condensers on the cardioid principle. The purpose of all forms is to give a ring of light which shall be of great aperture, and be as free as possible from chromatic and spherical aberration, and hence will form a sharp focus of the hollow cone upon the level where the objects are situated.

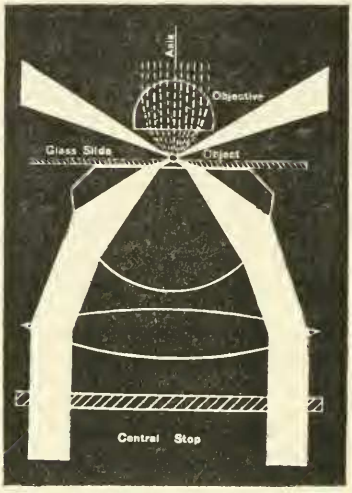

Fig. 6. Bright-field condenser with central stop to give dark-field illumination.

This is a sectional view showing the hollow cone of light focusing on the object and then continuing wholly outside the aperture of the objective.

The light deflected by the object into the objective is represented by broken lines.

The glass slide is in homogeneous contact with the top of the condenser, and the medium beyond the object is represented as homogeneous with glass.

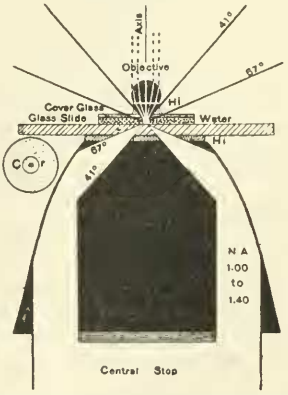

Fig. 7. Paraboloid condenser for dark-field illumination.

Axis—The principal optic axis of the microscope.

Central Stop—The opaque stop to cut out all light that would be at an aperture less than 1.00 NA.

Cover Glass—The cover for the object. For dry objectives it must conform to the objective, and with homogeneous objectives it must be less than their working distance in thickness.

C r—Face view of the top of the paraboloid showing the centering ring, the spot of white ink in the middle and the grains of starch for centering and focusing high powers.

Glass Slide—The slip of glass on which the object is mounted. It is connected with the top of the paraboloid by homogeneous liquid, and must be of a thickness to permit the focusing of the hollow cone of light upon the object.

Hi, Hi—Homogeneous liquid between the cover-glass and the objective and between the top of the condenser and the slide.

NA 1.00 to 1.40—The numerical aperture of the hollow cone of light focused on the object by the paraboloid. As indicated on the left this is represented by a glass angle of 41 to 67 degrees.

41° 67°—The limits of the angle of the rays in glass. Objective—The front lens of the objective. The light rays deflected by the object are indicated by white lines below and through the lens, then by broken, black lines above the front lens of the objective. Water—The mounting medium for the objects.

In this diagram the course of the rays from the paraboloid are indicated as if the objects were mounted in homogeneous liquid and that the rays passed beyond the focus into a medium homogeneous with glass.

TABLE SHOWING THE MAXIMUM ANGLE IN GLASS, AND THE CORRESPONDING NUMERICAL APERTURE OF THE LIGHT WHICH CAN PASS INTO MEDIA OF DIFFERENT REFRACTIVE INDEX ABOVE THE CONDENSER (FIG. 8-11)

	Angle in Glass	Numerical Aperture	Index of Refraction
1. Air over the condenser	41°	1.00	1.00
2. Water	61°	1.33	1.33
3. Glycerin	75° 15'	1.47	1.47
4. Homogeneous liquid	90°	1.52	1.52

In the reflecting as in the refracting condensers the central part of the light beam from the source is blocked out by a central stop and only a ring of light enters the condenser.

Immersion connection of condenser and glass slide bearing the specimen.—While the purpose of the reflecting condenser is to produce a very oblique beam of light for illuminating the objects, it is seen at once that the laws of refraction will prevent the light from passing from the condenser to the object unless the glass slide bearing the object is in immersion contact with the top of the condenser.

That is, for air (index 1.00) above the condenser, the rays in glass at 41°, NA 1.00 and less can pass from the condenser into the air and expand into a hemisphere of light in it (Fig. 8). Rays above 41° are totally reflected back into the condenser.

For water (index 1.33) above the condenser, rays in the glass at 61°, NA 1.33, and less can pass into the overlying water and make a complete hemisphere of light in it (Fig. 9). Rays above 61° are totally reflected back into the condenser.

For glycerin (index 1.47) above the condenser, rays in the glass at 75° 15', NA 1.47 and less can pass from the glass into the overlying glycerin and form a hemisphere of light in it (Fig. 10). All rays at a greater angle are reflected back into the condenser.

For homogeneous liquid (index 1.52) over the condenser, there is no limit to the angle of light that can pass from the condenser to it (Fig. 11).

Immersion Liquid between Condenser and Glass Slide. While water or glycerin answers fairly well it is recommended that homogeneous liquid be used in all cases. At first glance this would seem unnecessary for, as just stated the aperture of the light is limited by the medium of least refractive index between the condenser and the object. Thus objects mounted in watery fluids, and especially those mounted in air would seem to have the illuminating ray that could reach them limited by an aperture of 1.33 in one case and of 1.00 in the other (glass angles of 61° and 41°). This would be true if the objects were suspended in the water or in the air, but many of the particles are not suspended but rest on the glass slide, that is are in so-called *optical contact* with the slide. This being true, the angle of the light which can pass from the condenser to them depends upon their own refractive index, and not upon that of the mounting medium (air or water). This explains also why objects not in optical contact with the slide are rendered more visible by the homogeneous immersion contact of slide and condenser for the scattered light from the particles in optical contact helps to light up particles not in contact.

Another consideration also favors the use of the homogeneous immersion contact of slide and condenser, even for objects mounted in air. Physicists have found (see Wood) that beyond the critical angle, while all light is turned back into the denser medium, it does nevertheless pass one or more wave lengths into the rarer medium to

find, so to speak, an easier place to turn around in. If now any object is near enough the slide to fall into this turning distance of the totally reflected light it may be said to be in optical contact, and the light which meets it will pass into it instead of being totally reflected.

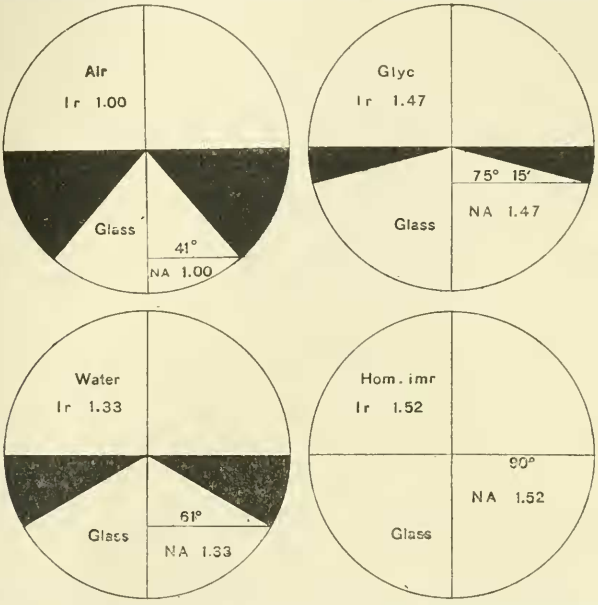

Fig. 8, 9, 10, 11. Diagrams showing the angle and numerical aperture of the light in glass to fill the entire hemisphere above, with overlying media of air, water, glycerin, or homogeneous immersion liquid.

As shown by the diagrams, the NA of the light in each case must equal the index of refraction (Ir) of the overlying medium to fill the overlying hemisphere with light. If the light is at a greater than the critical angle it is reflected back into the condenser. Such light is represented by black in 8, 9, 10. With homogeneous liquid (Hom. imr) above the condenser there is no critical angle.

It should be said in passing that the medium of least refractive index in the path of the light beam from the condenser determines the critical angle at which the light is wholly reflected, and hence determines the maximum angle of the illuminating pencil that can light the object, but this does not apply if the object is in optical contact with the glass (see below).

One can make a very convincing experiment to show the importance of remembering that some of the objects are in optical contact with the glass slide and hence may utilize light which could not pass

into the surrounding medium. If the upper face of the dark-field condenser is cleaned as perfectly as possible, and then lighted well, one can see no light emerging from the top except where the centering ring is situated or where there are some accidental scratches. If one dusts some starch, flour or other white powder on the clean surface, the particles which make optical contact with the glass will glow as if self-luminous. In case one wishes further evidence, the end of the condenser should be carefully cleaned, and a glass slide of the proper thickness connected with it by means of homogeneous liquid, then some flour or starch can be dusted on the slide and it will glow as did the particles on the top of the condenser. These demonstrations show well with the naked eye and with objectives up to 8 mm. (Fig. 7, Cr.)

Aperture of the Ring of Light in the Condenser. As the angle of the light illuminating the objects must be greater than can enter the objective employed it follows that the central part of the illuminating beam must be blocked out up to or beyond the aperture of the objective to be used. The greatest aperture rays possibly attainable depends upon the opticians ability to so design and construct the condenser that it will bring the remaining shell or ring of light to a focus. For those designed to be used with all powers, the aperture of this ring of light usually falls between 1.00 NA and 1.40 NA. As water and homogeneous immersion objectives have a numerical aperture greater than 1.00 NA. it follows that they could not be used for dark-field observation with their full aperture, because much of the light from the condenser could enter the objective, giving rise to a bright or at least a gray field.

Reducing diaphragms for high apertured objectives. As the lower limit in aperture of dark-field condensers is 1.00 NA, and sometimes even lower, it follows that a condenser for use with all objectives requires that none of them have an aperture over 1.00 NA. As all modern immersion objectives have an aperture greater than 1.00 NA, this aperture must be reduced by inserting a diaphragm in the objective.

The general law that the resolution varies directly with the aperture, and the brilliancy as the square of the aperture, holds with dark-field as with bright-field microscopy. In order to determine by actual experiment with various dark-field condensers the best aperture of the diaphragm to select, the writer requested, the Bausch & Lomb Optical Company and the Spencer Lens Company to supply

reducing diaphragms for their fluorite, homogeneous immersion objectives ranging from 0.50 NA. to 0.95 NA. As measured by me these diaphragms ranged from slightly above 0.50 NA, to 0.97 NA. These varying apertures were tested on each condenser, using the same light and as nearly as possible identical preparations (i.e., fresh blood mounted on slides of the proper thickness). It seemed to the

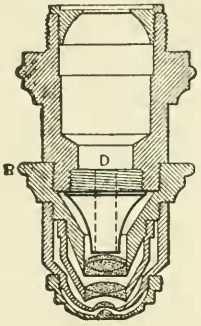

Fig. 12. Large aperture objective with diaphragm to reduce the aperture to less than 1.00 NA. (From Chamot)

D Funnel-shaped reducing diaphragm in the interior of the objective above the back lens.

writer that the law of aperture as stated above held rigidly. The question then is, which aperture shall be chosen if but one diaphragm is available? It seemed to the writer that the one of 0.80 NA should be chosen, at least for these fluorite objectives. If three are to be had the range should be 0.70, 0.80 and 0.90. The reason why one over 0.90 is not recommended is because some examples of the best of the dark-field condensers tested, seemed to have their lower limit somewhat below 1.00 NA, and hence the field could not be made completely dark with the diaphragm of 0.97 NA. With others, however, the field was as dark with this large aperture as with the lower apertured diaphragms.

A considerable range of reducing diaphragms for the homogeneous immersion objectives is recommended because all experience brings home to the worker with the microscope the conviction that some structures show better with the lower apertures and some with higher ones, and it is believed from considerable experience that the same fundamental principles hold in dark-field as in bright-field microscopy.

Lighting for Dark-Field Microscopy

As is almost self-evident, only a very small amount of the light passing through the condenser to the objects is deflected by the objects into the microscope, consequently the source of light must be of great brilliancy or there will not be enough to give sufficient light to render the minute details of the objects visible, when high powers are used. This visibility of minute details involves three things: (1) The aperture of the objectives; (2) The aperture of the illuminating pencil; (3) The intensity of the light.

The most powerful light is full sunlight. Following this is the direct current arc, the alternating current arc and then the glowing filament of the gas-filled or Mazda lamps.

The reflecting condensers are designed for parallel beams consequently the direct sunlight can be reflected into the condenser with the plane mirror of the microscope. If the arc lamp, a Mazda lamp, or any other artificial source is used a parallelizing system must be employed. The simplest and one of the most efficient is a plano-convex lens of about 60 to 80 mm. focus with the plane side next the light and the convex side toward the microscope mirror (Fig. 14) i.e., in position of least aberration. This is placed at about its principal focal distance from the source whether that be arc lamp, Mazda lamp, or any other source and the issuing beam will be of approximately parallel rays. These can then be reflected up into the dark-field condenser with the plane mirror.

Lamps for Dark-Field Microscopy

Up to the present the small arc lamp (Fig. 13), using 4 to 6 amperes is practically the only one considered really satisfactory. There is no question of the excellence of the direct current arc. The alternating current arc has two equally bright craters which renders its use somewhat more difficult.

For most of the work in biology the arc gives more light than is comfortable to the eyes; but a still greater objection is that with the burning away of the carbons the source of light is constantly shifting its position, and hence the quality of the light varies from minute to minute. A third difficulty for hand-feed lamps is that one must stop observation frequently to adjust the carbons.

In spite of all these difficulties, however, the arc lamp is indispensable if one desires to attack all the problems for which the dark-field microscope is available.

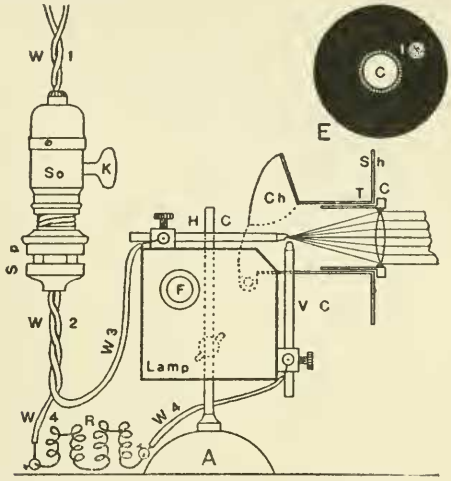

Fig. 13. Small arc lamp for dark-field illumination (From *Optic Projection*)

This figure is to show the wiring necessary and the arrangement of the arc and lens to give a parallel beam.

A—Heavy base of the lamp support. By means of a clamp the lamp can be fixed at any desired vertical height. HC and VC, the horizontal and vertical carbons. The HC must be made positive. F, the wheels by which the carbons are fed.

TC—The tube containing the condenser. The condenser in the inner tube can be moved back and forth to get a parallel beam. Sh, black shield, see E.

E—Black shield at the end of the lamp tube (Sh). It serves to screen the eyes and to show when the spot of light is thrown back by the mirror into the parallelizing lens.

W1, W2, W3, W4—The wires of the circuit passing from supply to the upper carbon (HC) and from the lower carbon (VC) to the rheostat, and from the rheostat back to the supply in W1. Never try to use an arc lamp without inserting a rheostat in the circuit. As shown, it forms a part of one wire. It makes no difference whether it is in the wire going to the upper or to the lower carbon, but it must be in one of them.

6-Volt Headlight Lamp.—Next to the arc lamp in excellence for dark-field work is the 6-volt gas-filled headlight lamp (Fig. 14). The reason of this excellence is that the filament giving the light is in a very close and small spiral not much larger than the crater of the small arc lamp, and hence approximates a point source of light.

The brilliancy is also very great as the filament is at about 2800° absolute. The two sizes that have been found most useful by the writer are the bulbs of 72 watts and those of 108 watts. For the bulb of 108 watts a mogul socket is essential; for the 72 watt bulb the ordinary socket is used.

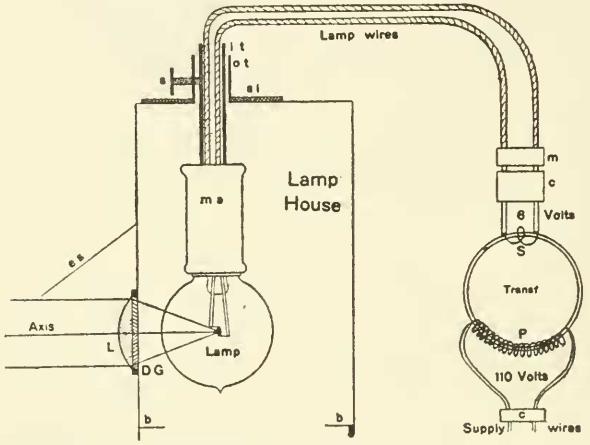

Fig. 14. Diagram of headlight lamp and transformer for dark-field illumination (About one-sixth natural size).

Axis—Axis of the parallel beam from the lens (L).

Lamp—The 6-volt, 108 watt headlight lamp with its very small, close filament centered to the axis of the lens. It is in a mogul socket (ms) and can be centered vertically and horizontally by the inner and outer tubes and set screw (it, ot, s), and the brass slide (sl).

Lamp House—The metal container for the lamp. (b b) Bafle plates near the bottom to help avoid stray light. At the left over the lens (L) is the sloping eye shade. L D G—Parallelizing lens cemented to polished daylight glass.

Lamp wires—The large wires from the transformer (Transf.) to the lamp (Double heater wires are good).

m c—Mistakeless connection between the lamp wires and the transformer (Transf). This is a Manhattan stage connector, and is different from anything else in the laboratory and therefore the lamp can never be connected with a 110 volt circuit and burn out the lamp. Of course any other wholly different connection would answer just as well.

Transf.—Diagram of a step-down transformer. As there are 18 coils around the soft iron ring on the Primary (P) or 110 volt side, and but one coil around the Secondary (S) side, the voltage is stepped down 18 times, or from 110 to 6 volts. In an actual transformer the coils would be far more numerous, but in this proportion. If the transformer were connected wrongly, i.e., with the lamp wires connected with

the primary (P) side, and the 110 volt supply with the secondary (S) side, it would then be a step-up transformer, and raise the 110 volts 18 times—with disastrous results. C, separable connection for the 110 volt supply wires.

The only difficulty with these lamps is that as they are for a 6 volt circuit it is necessary to use a step-down transformer if one has an alternating current with a voltage of 110 or of 220, as is usual.

If one has a direct current of 110 or 220 voltage, then it is necessary to use a storage battery, in general like those used for the lighting and ignition systems of automobiles. As a transformer uses up but a very small amount of energy it will be readily seen that in stepping down the voltage the amperage is correspondingly raised from the general law that the wattage is the product of the voltage into the amperage, and knowing any two the third may readily be found.

For example with the 72 watt lamp, if the voltage is 6 the amperage must be 72/6 or 12 amperes. With the 108 watt bulb the amperage must be $108/6 = 18$ amperes.

The heating of the filament is determined by the amperage, and also it must be remembered that the conductor of an electric current must be increased in due proportion for an increased amperage, consequently in the transformer the wires joining the 110 volt line is small because a very small amperage is necessary to give a large wattage; while from the transformer to the lamp the conducting wires must be large, to carry without heating the amperage necessary with the low voltage (6) to give the large wattage (108 or 72).

For the 18 amperes of the 108 watt bulb, the Fire Underwriters specifications call for wire of No. 12 or No. 14 Brown and Sharp Guage, i.e., wire 1.6 to 2 mm. in diameter or a cable composed of smaller wire having the same conductivity. This specification is for continuous service. In wiring the headlight lamp from the transformer, so called *heater cable* is good, provided one uses a double cable, that is the entire cable for each wire. This is easily done by removing the insulation at the ends and twisting the two strands together, then it can be treated as one wire and the two thus treated used to join the lamp to the mistakeless connection (m c, Fig. 14, 15) of the transformer. As the resistance is small in these large conductors the full effect of the current remains to make especially brilliant the glowing lamp filament, and brilliancy is what is needed for this work.